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16. ABSTRACT

This discussion is directed to users of the Climatological Dispersion Model (CDM) who are interested in that model's sensitivity to the manner in which the area-soure emissions are specified. The CDM was used to estimate annual average SO_2 concentrations from area-source emissions for 13 locations in the St. Louis metropolitan area for 1976. The SO_2 area source emissions inventory used was developed as part of the St. Louis Regional Air Pollution Study; this inventory specifies the SO_2 emissions over a 200 km east-west by 140 km north-south region. We examined the variation in concentration estimates due to variation in the degree of detail with which the spatial changes in the emissions were specified and due to variation in the areal extent of the emissions modeled. We observed that, for the receptor locations nearest the larger area-source emissions, the concentration estimates were quite sensitive to the detail with which the spatial variation in emissions was specified. Furthermore, we observed that the area-source concentration estimates were dominated by the portion of the emissions inventory having the majority of emissions.

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JOURNAL ARTICLE

A Sensitivity Analysis of the Treatment of Area Sources by the Climatological Dispersion Model

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The area-source contributions calculated by the Climatological Dispersion Model (CDM) are sensitive to the size of the grid square used to specify the area source emissions. The authors recommend estimation of highest long term concentrations be accomplished by specifying the emissions with as small a grid size as convenient in that portion of the region having the largest area-source emissions.

These conclusions are based on a sensitivity study employing the SO_2 emissions inventory developed as part of the St. Louis Regional Air Pollution Study. This inventory specifies the SO_2 emissions over a 200-km (east-west) by 140-km (north-south) region. The CDM was used to estimate annual average SO_2 concentrations from area-source emissions for 13 locations in the St. Louis metropolitan area for 1976. Although the area source emissions constituted only 3.5% of total area and point source emissions, estimated concentrations from area sources ranged from 14 to 67% of the total concentration estimated at the 13 sites. The median estimated impact from area sources was 32% of the total from both point and area sources. We examined the variation in concentration estimates due to variation in the degree of detail with which the spatial changes in the emissions were specified and due to variation in the areal extent of the emissions modeled. We observed that, for the receptor locations nearest the larger area-source emissions, the concentration estimates were quite sensitive to the detail with which the spatial variation in emissions was specified. Variations in calculated impact of greater than 30% were observed depending on whether a grid size of 1, 2, 5, 10 or 20 km was selected. We observed that the area source concentration estimates were dominated by the portion of the emissions inventory having the majority of emissions. Neglecting 35% of the area source emissions on the outer fringes of the region and thereby reducing the modeled inventory to a 50 by 50-km square, gave nearly identical results to modeling the entire inventory.

Based on the wide variability in calculated concentrations attributable to user-selected parameters, the authors strongly recommend that sources be modeled as point sources and only minor indeterminate emissions be modeled as area sources.

This study investigated the sensitivity of the Climatological Dispersion Model's estimates of annual SO_2 concentrations to the degree of detail with which the spatial variation and extent of the area-source emissions inventory are specified. The basis of the Climatological Dispersion Model (CDM) is that the emissions and the meteorological conditions can be treated as independent.[1] This allows calculation, without use of short-term values, of long-term seasonal or annual average concentrations for an urban area.

The meteorological conditions are specified by a joint-frequency function which describes the joint occurrence of winds within 16 wind direction sectors, wind speeds within six wind speed categories, and stability within six Pasquill stability categories. Average (annual or seasonal) values of emission rate and source emission characteristics are used to characterize the point-source and area-source emissions. The mathematical details are fully explained in the CDM User's Guide.[2]

For this study, the important feature of the modeling computations is the manner in which the area-source emissions are treated. The average concentration at a particular receptor due to area-source emissions involves the computation of an average area-source emission rate, q_k, at various increments of distance upwind from the receptor. Smaller increments are used close to the receptor as indicated in Table I. Angular integration to determine q_k using the trapezoidal rule is carried out numerically at each distance selected upwind. The average concentration is then determined by integration.

Table I. Increments of distance, ρ, used in numerical evaluation of the average SO_2 concentration from the area-source emissions.

Distance (m)	Increment (m)
$0 < \rho \leq 2500$	250[a]
$2500 < \rho \leq 5000$	500
$5000 < \rho \leq r_{max}$[b]	1000

[a] This initial increment is specified as input data to the model. The other increments are multiples of the initial increment.
[b] Incrementing stops when the distance from the receptor extends beyond the specified bounds of the area-source emission grid.

As q_k is determined using a sample of values of area-source emission rates, Q, along the sector arc at each sampled distance, the degree of detail used in specifying Q can affect the values computed for long-term average concentration from area sources. In this study, the variation in the average concentration at selected receptor locations was investigated by either smoothing the original gridded area-source emissions inventory into a larger grid spacing, or by limiting the region over which the area-source emissions were defined.

For the emissions inventory, we chose the 1976 SO_2 inventory developed as part of the St. Louis Regional Air Pollution Study (RAPS).[3] The area source inventory is specified for a 140-km north-south by 200-km east-west area. The point source inventory consists of 196 sources. For the point sources, the annual average emission rate ranged from 4294 g/s to 0.01 g/s, with 90% of the emissions accounted for by 20 sources.

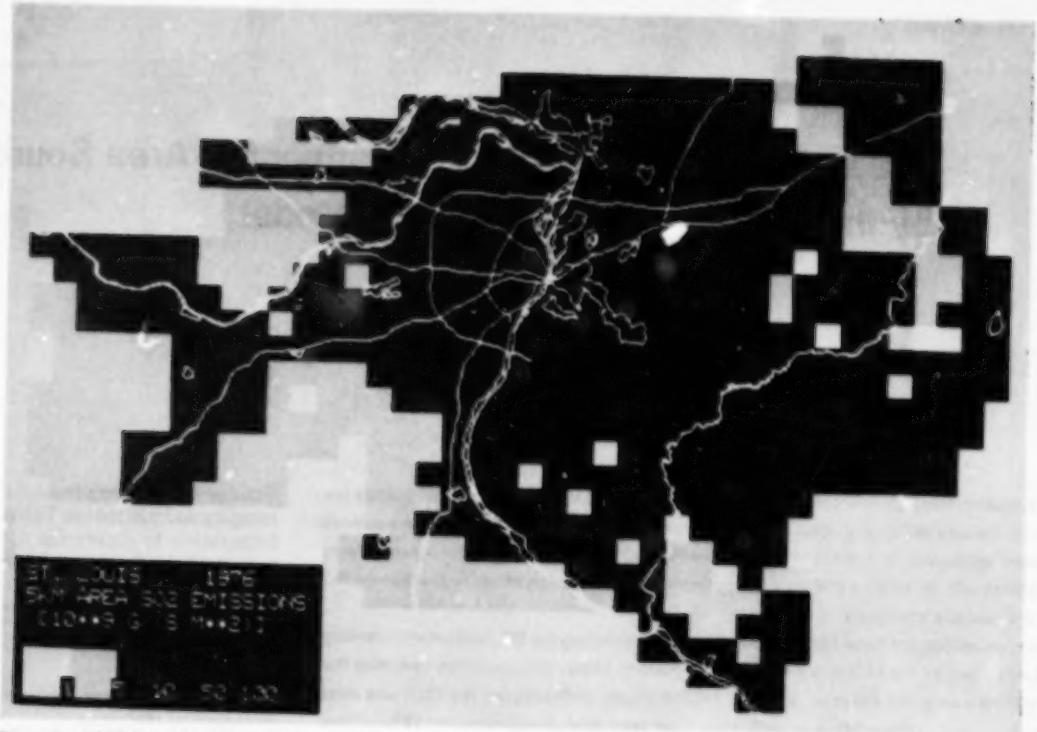

Figure 1. RAPS St. Louis 1976 annual-averaged area-source SO_2 emissions inventory depicted using a basic grid-square size of 5 km. The coordinates of the southwest corner of the depicted area are 640 km (east-west) and 4190 km (north-south).

The total emissions from all point sources was 28.71 kg/s and from all the area sources was 1.05 kg/s. Only 3.5% of the emissions are distributed to the area sources yet, as we discuss later, these emissions are estimated to account for over 25% of the annual concentration for those receptors within the city and in some instances 50% or more.

Care needs to be exercised in specifying the area-source emissions, for even though they amount to only 3 to 4% of the total emissions, they can have considerable impact on the modeling estimates.

Considering the detail employed in specifying the area-source emissions and the areal extent over which the emissions are specified, this data base seemed an appropriate choice for our sensitivity analysis. Model evaluation studies employing the CDM to estimate concentrations in the vicinities of St. Louis,[4] New York,[5] and Copenhagen[6] suggest that the CDM is applicable for long term SO_2 concentrations for receptors within an urban area, even though some of the emissions may be from sources in nearby rural areas. The 1976 St. Louis RAPS data base includes both rural and urban emissions. As this is a sensitivity analysis, we have chosen to model all emissions as being from an urban area. Most of the emissions are urban and, as discussed later, we found that the urban emissions dominated the estimated concentrations even for locations well away from the downtown area.

Data Analysis and Results

The CDM uses a rectangular grid array of uniformly sized squares to overlay the region of interest. The purpose of this grid is to catalog the emissions inventory by area sources. There is some flexibility in the size of the grid squares used to define the area sources, as the model will accept information on emissions from squares having sides that are integer multiples of the user-defined basic grid-square size. Thus, if the basic square has length s, emissions information for a square of sides $4s$ will be distributed uniformly into 16 basic squares.[2]

The 1976 St. Louis RAPS data base specifies the SO_2 area-source emissions over a 200-km east-west by 140-km north-south region centered on the city of St. Louis (Figure 1). The basic grid square size is 1 km. Larger squares with sides of up to 10 km are used to specify some of the emissions. Figure 1 depicts the spatial variation of the annual-averaged SO_2 area source emissions using a 5-km grid.

The meteorological data used in this analysis represent a synthesis of data from various sources. The 25-station RAPS air monitoring network collected data on the criteria pollutants (including SO_2 at 13 of these stations) and meteorological data (including wind speed, wind direction, and ambient air temperature). For each hour of the year, the average wind speed, wind direction, and air temperature were interpolated from the 25 monitoring stations. Ceiling and cloud height information was extracted from National Weather Service hourly observations at Lambert Field and was used to estimate a Pasquill stability category[7] for each hour. Using these data, the meteorological joint frequency function was computed. Daily morning and afternoon mixing depths were computed from the RAPS radiosonde and acoustic sounder data. From these values, the St. Louis 1976 average minimum and maximum mixing depths were calculated (691 m and 1246 m, respectively).

Several initial model runs using the 1-km-gridded emissions were made in order to determine the optimum value for the initial increment (DELR in the model) and to determine the optimum number of samples (DINT) of area-source emission rate, Q, to be used to evaluate q_k. The modeling results are sensitive to the choices made for DINT and DELR. We chose to use the smallest value of DINT and largest value of DELR that yielded results within 1 to 2 $\mu g/m^3$ of those generated using larger values for DINT or smaller values for DELR. Some guidance is given to selecting input values in Addendum to User's Guide for Climatological Dis-

Table II. Measured and estimated annual SO_2 concentrations. Values listed for each receptor are: measured concentration (CO), estimated contributions from point sources and area sources (EP and EA) and the total estimated concentration (ET). To aid in comparing the measured and estimated concentrations, values are listed for the residual (R1 = ET − CO) and the percentage error (R2 = 100-R1/CO).

Station ID	Hours of valid data	Emission grid coordinates (km) East	North	Concentration ($\mu g/m^3$) CO	EP	EA	ET	R1	R2
Inner city[a]									
101	6088	744.18	4279.86	36.8	31	63	94	57	154
103	7369	747.59	4282.47	26.2	32	23	55	29	112
104	6686	747.31	4277.30	86.1	30	33	63	−23	−27
105	7206	743.71	4276.45	34.9	24	24	48	13	37
106	6433	738.66	4277.57	38.7	24	27	51	12	30
Outer City[b]									
108	7284	748.41	4291.10	28.5	35	13	48	19	66
113	6780	737.74	4289.92	27.2	25	14	39	12	44
Suburb[c]									
114	7083	744.32	4297.46	23.3	28	9	37	14	60
115	7165	757.11	4297.80	21.7	41	7	48	26	118
116	7571	762.78	4290.08	17.4	22	8	30	13	26
120	7292	723.08	4285.91	19.0	13	6	19	0	0
121	6913	732.41	4302.38	23.3	18	5	23	0	0
Rural[d]									
122	6741	741.63	4329.22	18.9	18	3	21	2	10

[a] Less than 6.5 km from Station 101.
[b] From 6.5 to 12.5 km from Station 101.
[c] From 12.5 to 25.5 km from Station 101.
[d] More than 25.5 km from Station 101.

persion Model.[8] The values best suited for a given analysis can only be found through experimentation. We determined that to use more than five evenly spaced samples of Q along each 22.5° arc (DINT = 4) or to use an initial increment of less than 250 m (DELR = 250) did not significantly alter the estimates of annual concentration. Thus all succeeding analyses employed an initial increment of 250 m and five samples of Q along each arc. We further decided to limit the receptor locations to the 13 stations at which SO_2 measurements were made.

Table II lists the estimated and measured annual SO_2 concentrations. The modeled emissions include all of the area-sources, using a 1-km grid, and all of the point sources. The surprising result that emerges from Table II is the strong contribution from the area-source emissions to the estimated annual average concentrations. This result is not unique to this particular modeling inventory. Indeed, these results should serve to warn readers to avoid the use of characterizing SO_2 emissions as being from area-sources as much as possible. This is because most of the algorithms employed for characterizing dispersion from area-sources make simplifying assumptions in order to reduce the time needed to make the computations.

Valid SO_2 measurements were not available for every hour of the year; as a result, the annual means were calculated by averaging the data that were available. The background concentration was assumed to be zero for both the measurements and the model estimates. The percentages of valid data obtained at these 13 stations ranged from 69% (Station 101) to 86% (Station 116); the average was 79%. For 10 of the 13 stations, the model overestimated the measurement by an average factor of 1.38. The extreme overestimate occurred for Station 101 (2.54 times the measured concentration). The only underprediction occurred for Station 104 (0.73 of the measured concentration). Here we suspect that a source increased its emissions during the last two months of the year.[9]

Model estimates for these 13 stations showed a mean error of 56%. The error ranged from −27% to 154% (Stations 104 and 101, respectively). The bias to overestimate concentrations by an average of 13 $\mu g/m^3$ may be explained partially by the setting of the SO_2 half-life at infinity (no loss of SO_2 during transport) so that the results would highlight the CDM's sensitivity to variations in the area source inventory detail and extent. Specifying a half-life of 3 h would have reduced the CDM's estimates by 8 $\mu g/m^3$ on average.

Basic Grid-Square

Increasing the grid size of the emissions inventory increases the similarity between adjacent grid square emissions. Much of the detail of the emissions patterns is thereby lost in the attendant averaging process. The very high emission rates in the downtown areas are reduced, and the rates in the adjacent areas are increased slightly. Table III presents a breakdown of the distribution of SO_2 area-source emission rates for several basic grid square sizes.

Table IV summarizes the configurations of the area-source inventory used

Table III. Distribution of annual average SO_2 emission rates[a] for several basic grid-square sizes.

Q, g/(s m²) Lower bound	Upper bound	Number of occurrences in each Q interval Basic grid-square size (km) 1	2	5	10	20
	1×10^{-10}	0	0	0	0	1
1×10^{-10}	5×10^{-10}	0	3	0	2	0
5×10^{-10}	1×10^{-9}	0	16	21	3	2
1×10^{-9}	5×10^{-9}	5374	1260	158	37	10
5×10^{-9}	1×10^{-8}	2409	648	109	33	8
1×10^{-8}	5×10^{-8}	6339	1677	253	83	23
5×10^{-8}	1×10^{-7}	1766	461	86	16	5
1×10^{-7}	5×10^{-7}	1151	290	54	14	4
5×10^{-7}	1×10^{-6}	145	38	8	3	1
1×10^{-6}	5×10^{-6}	138	40	6	2	0
5×10^{-6}	1×10^{-5}	14	3	0	0	0
1×10^{-5}		3	0	0	0	0
Total nonzero grids		17339	4436	695	195	54
Total zero grids		10661	2564	425	87	16
Total grids		28000	7000	1120	280	70

[a] 1976 St. Louis RAPS area-source emissions inventory.

Table IV. Summary of area-source configurations modeled.

Run No.	Coordinates of southwest corner of emission grid (km) East	North	Emission grid size (km) East-west	North-south	Basic grid-square size (km)	Area-source emissions modeled (%)
1	640	4190	200	140	1	100.0
2	640	4190	200	140	2	100.0
3	640	4190	200	140	5	100.0
4	640	4190	200	140	10	100.0
5	640	4190	200	140	20	100.0
6	650	4190	190	140	1	99.9
7	675	4190	150	140	1	97.6
8	700	4225	100	100	1	89.8
9	725	4250	50	50	1	65.0
10	730	4255	40	40	1	59.0
11	735	4260	30	30	1	52.2
12	740	4265	20	20	1	30.8

for 12 model runs. The results of Runs 1 through 5 are presented in Table V, and the results of Runs 6 through 12 are presented in Table VI. Only the contributions from the area-sources are presented in these and subsequent tables. Runs 1 through 5 employed various basic grid-square sizes. (Figures 1 and 2 can be used to better appreciate the receptor locations relative to each other and to the emissions inventory.) We observed that best results were obtained using the smallest grid square size of 1 km. The concentration estimates for Stations 101, 104, and 106 changed the most in response to increases in the basic grid-square size from 1 km to 20 km. These sites are adjacent to those 1-km grid squares having the largest annual SO_2 emission rates. As can be seen in Table III, increasing the grid-square size not only reduced the occurrence of high emission rates in the downtown area but also reduced the occurrence of zero emission rates in the suburbs. Fewer areas with zero emission rates caused an increase in the concentration estimates at Stations 120, 121, and 122 (Table V) as the grid-square size was increased from 1 to 20 km.

Table V. Estimated annual SO_2 concentrations ($\mu g/m^3$) from area-sources as a function of basic grid-square size.

Station ID	Basic grid-square size (km) 1	2	5	10	20
101	63	50	42	29	21
103	23	24	24	27	22
104	33	32	33	28	21
105	24	28	35	28	20
106	27	27	26	18	14
108	13	13	13	14	15
113	14	14	15	18	12
114	9	9	9	10	10
115	7	8	7	8	10
116	8	8	8	9	9
120	6	6	6	6	10
121	5	5	6	6	6
122	3	3	3	3	4

Sensitivity to Portion of Area-Source Inventory Modeled

Runs 6 through 12 (Table VI) examined the sensitivity of the results to the portion of the inventory modeled. Most of the emissions appear to occur in the vicinity of downtown St. Louis (Figure 1). The 20-km stippled area in Figure 2 indicates the portion of the inventory modeled in Run 12. Thirty-one percent of the total SO_2 area-source emissions occur within this area. So long as the modeled emissions included this downtown 20 km by 20 km portion of the inventory, satisfactory results were obtained.

The results of Runs 6 through 9 (Table VI) show very little change in the estimated concentrations when only 65% of the total emissions were modeled. The results of Run 12 (Table VI) for the 20-km by 20-km portion of the inventory suggest that these emissions accounted for 17 to 33% of the concentrations estimated for the rural stations (120, 121, and 122) and for 75 to 90% of the concentrations estimated for the downtown stations (101, 103, 104, and 105).

Table VII presents the results of a series of analyses that used the entire 1-km-gridded emissions inventory, with a limited upwind extent of the area-source integration. This analysis, coupled with the results presented in Table VI, addressed the question of whether it is best to model the portion of the inventory near the receptor or whether it is best to model the portion that accounts for most of the emissions. It was determined that better results were obtained by modeling the portion of the region accounting for most of the area-source emissions than concentrating only on those area source emissions nearest the receptor. The concentrations estimated for Stations 101 through 105 are within 13 $\mu g/m^3$ of those computed using the entire area-source inventory when area sources within 5 km are considered, concentrations are within 2 $\mu g/m^3$ when area sources within 15 km are considered. For these same receptors, using a fixed 50-km by 50-km portion of the entire inventory (Run 9 in Table VI), the estimated concentrations

Table VI. Estimated annual SO_2 concentration ($\mu g/m^3$) from area-sources for subportions of the emissions inventory centered on downtown St. Louis.

Run No.:	1	6	7	8	9	10	11	12
Percent of total area:	100	95	75	36	9	6	3	1
Percent of total emissions:	100	99	98	90	65	59	52	31
Station ID	Area-source contribution ($\mu g/m^3$)							
101	63	63	63	63	62	62	61	57
103	23	23	23	23	22	22	22	18
104	33	33	33	33	32	32	32	29
105	24	24	24	24	23	23	22	18
106	27	27	27	27	26	26	25	10
108	13	13	13	13	12	12	10	6
113	14	14	14	14	13	12	11	5
114	9	9	9	9	7	7	6	4
115	7	7	7	7	6	5	4	2
116	8	8	8	8	6	6	5	2
120	6	6	6	6	4	3	3	1
121	5	5	5	5	4	4	3	1
122	3	3	3	3	2	1	1	1

Table VII. Estimated annual SO_2 concentrations ($\mu g/m^3$) from area-sources for subportions of the emission inventory centered on each receptor position.

Station ID	Distance limit imposed on area-source integration (km)				
	2.5	5.0	10.0	15.0	20.0
101	45	53	59	61	62
103	4	10	19	21	22
104	16	23	29	31	32
105	5	12	20	22	22
106	9	17	23	25	26
108	1	3	4	9	11
113	1	2	6	11	12
114	0	0	1	2	6
115	0	1	2	3	4
116	1	1	2	3	4
120	1	1	2	2	4
121	0	0	1	1	2
122	0	0	0	0	0

are within 2 $\mu g/m^3$ of those obtained using the entire inventory.

Conclusions

This study showed the CDM to be sensitive to the degree of detail used to specify the spatial variation in SO_2 emission rates. The effects of combining the original inventory into emission grids of resolution greater than 1 km were especially noticeable for receptor locations in the vicinity of the strongest area-source emissions. Reducing the modeled inventory from its original size of 200 km east-west by 140 km north-south to a size of 100 km by 100 km, centered on the larger area-source emissions, resulted in no change in the computed concentrations. A further reduction to a 50 × 50 km (Run 9) provided estimates that were within 1 to 2 $\mu g/m^3$ of those obtained by modeling all the area-source emissions.

The 50-km by 50-km area encompassed all but one (Station 122) of the receptor locations. It was not clear whether Run 9 gave favorable results because the modeled portion of the inventory included the major area-source emissions or because most of the emissions near each receptor were included. To resolve this question, a series of runs was made for each receptor in which the modeled portion of the inventory was centered on the receptor position rather than on the area of highest emissions. These results suggested that, for the receptor locations furthest from the downtown area (Stations 120, 121, and 122), less than 35% of the total concentration resulted from area-source emissions within 15 km of the receptors. The portion of the inventory having the highest emissions appeared to have more effect on the concentrations modeled for these receptors.

We conclude that, in modeling area-source concentrations, the CDM is most sensitive to the large area-source emissions and to the detail used to specify those emissions. To a lesser extent, the model is sensitive to the spatial extent of the emissions included in the analysis. These results suggest that in order to estimate the highest long-term concentrations, it is most efficient to concentrate on that portion of the region having the largest area-source emissions and to specify the spatial variation of those emissions in as much detail (i.e., with the smallest grid size) as convenient.

It must be recognized that area-source algorithms, such as the narrow plume concept or the virtual plume approximation, are gross simplifications of the complex dispersion that occurs from near-surface releases of emissions. When using such area-source algorithms, the best course to pursue would be to so structure the emission characterization that the area-source contribution is truly a minor portion of the total calculated impact from all emissions. Most existing area-source inventories fail to meet this goal, as was found to be the case for the SO_2 inventory employed in this sensitivity study. Hence, the more typical problem is learning to cope with existing characterizations of emissions. It would be convenient if we could counsel regarding what portion of the inventory to include in an analysis, what grid size to use and what values to use for DINT and DELR. Such is not possible with sensitivity results from only one emission inventory and we suspect that such detailed guidance would be found in error more often than not. The results of this sensitivity study suggest that use of

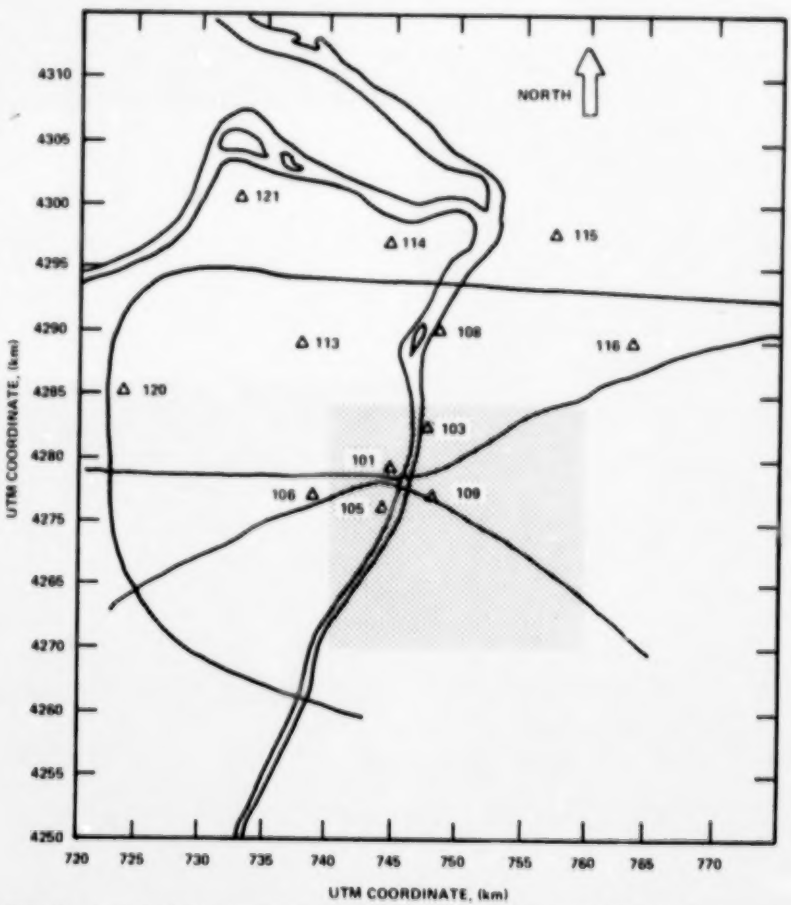

Figure 2. Location of the SO_2 monitoring stations in the vicinity of downtown St. Louis. Thirty-one percent of the area-source emissions occur in the 20-km by 20-km area shown.

the entire inventory, with as much detail as allowed in its construction, is a wise course of action. It seems that if an inventory is deficient in having partitioned too much of the emissions as area-sources, smoothing or regrouping of the emissions only serves to exacerbate the problem.

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